

2012 International Symposium on Safety Science and Technology Size effect on explosion intensity of methane-air mixture in spherical vessels and pipes

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Abstract

Size effect on explosion intensity of methane-air mixture in spherical vessels and pipes was studied in this paper. The experimental results suggested diameter of the spherical vessel, the length of connection pipes of single vessel and the length of connection pipes between two spherical vessels played a significant role in explosion intensity of methane-air mixture in spherical vessels and pipes. The maximum explosion pressure was almost constant, while the maximum rate of pressure rise decreased with an increasing diameter of the vessel. The maximum explosion pressure and the maximum rate of pressure rise in single vessel with connection pipes both decreased due to the increase of the length of connection pipes. There was a linear relationship between explosion intensity and the length. And the maximum explosion pressure and the maximum rate of pressure rise appeared at the end of connection pipes. For linked vessels, the explosion intensity in secondary vessel increased with an increasing length of connection pipes with linear relationships. The conclusions provided important references for safety design of explosion venting and explosion resistance.

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Keywords: vessels and pipes; explosion intensity; size effect; vessel diameter; pipe length

1. Introduction

During the industrial process, there exist run-away reactions and defects of reactors or pipes, which can cause fire and explosion accidents, resulting in a great loss of casualty and property. But the shapes and sizes of the vessels and the connection style of vessels and pipes are various in different technical processes, which can lead to different accident consequences[1]. The explosion characteristics of gas or dust change with the shapes of sizes of vessels and pipes, which is called size effect of gas or dust explosion[2-3].

Previously published researches about size effect of gas explosion at home and abroad are mainly focused on mine laneway with full sizes. The researches about size effect of gas explosion in reactors and pipes are little and lack of systematicness. And numerous studies on reactors and pipes with small size are concentrated on the gas nature, transmission law of the gas explosion, obstacles, etc[4-6]. And all the wall effect, pressure accumulation effect and corner effect, are also the influence of the structures and the sizes of containers or pipes in essences[7-10]. In addition, the current safety design of anti-explosion and explosion venting of containers or pipes, are guided through simulation experiment dates and traditional theory calculation models, that ignoring the influence of the structures and sizes of containers and pipes[11-13]. So this paper chose to study size effect of gas explosion intensity in spherical vessels and pipes, providing important scientific basis for anti-explosion and explosion venting of containers and pipes.

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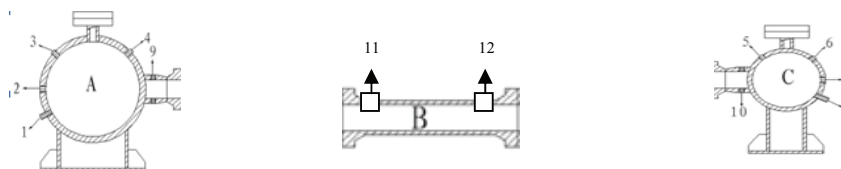
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2. Experimental apparatus

Experiment devices have two spherical vessels and three segments of pipes. The big vessel is with the size of $D=600\text{mm}$ and $V=113\text{L}$, and the small vessel with the size of $D=350\text{mm}$ and $V=22\text{L}$. Each pipe is with the size of $L=2\text{m}$ and diameter $D=60\text{mm}$. Flanges are welded in spherical vessels and pipes, and the positions of interfaces of pressure sensor, vacuum-pressure gauge, igniter and gas inlet, are shown in fig. 1. .

Ignition device is a high-energy electronic ignition (Model Number: XDH-6L) of which ignition energy is 6 J. Gas-distributing system is a gas sample compounder (Model Number: SY-9506) using to confect methane (10%) and air(90%). Date acquisition system is USB date acquisition instrument (Model Number: DEWE-43) and supporting analysis software using to test explosion pressure.



A—big vessel; B—pipe; C—small vessel; 1,8—gas inlet; 3,6—ignition; 2,7,9,10,11,12—pressure transducer; 4,5—vacuum-pressure gauge

Fig. 1. Schemes of spherical vessels and pipes.

3. Results and discussion

3.1. Size effect of changing diameters of spherical vessels on explosion intensity

Experiments were implemented in two spherical vessels, ignited in the center of spherical vessels. The ducts of spherical vessels were closed by stop-valves. Fig. 2. and Fig. 3. show the influence of diameters of spherical vessels on explosion intensity in spherical vessels. The maximum explosion pressure in the big vessel is 0.698 MPa, which in the small vessel is 0.699 MPa, and two values are equal ignoring the error. The maximum rate of pressure rise in the big vessel is $13.913\text{ MPa}\cdot\text{s}^{-1}$, which in the small vessel is $22.899\text{ MPa}\cdot\text{s}^{-1}$.

The spherical vessels are central-symmetric and there is not any obstacle in the spherical vessels. Then according to the theories of flame and shock wave propagation and thermodynamics[14-16], the restrictions of pressure wave by any curve are similar, the local changes of explosion flow field caused by the change of gas flow state are similar, the influence parameters of thermal conductive cooling heating are also similar. Therefore, there is no disturbance during the process of explosive pressure wave transmission. And the increase of explosion pressure is only relevant with the heating effect of explosion and thermodynamics. As a result, the maximum explosion pressure remains unchanged along with changes of the diameter. However, the maximum rate of pressure rise increased with the increase of the diameter of spherical vessels.

Thus it comes to the conclusion that changes the diameter of containers can produce size effect on methane-air mixture explosion intensity: changes of geometry size of containers, the maximum explosion pressure remaining unchanged, the maximum rate of pressure rise decreasing with the increase of the diameter of containers.

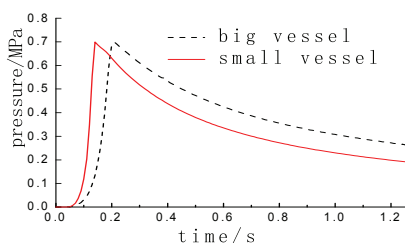


Fig. 2. Curve of pressure-time in spherical vessels ignited in the center of vessels.

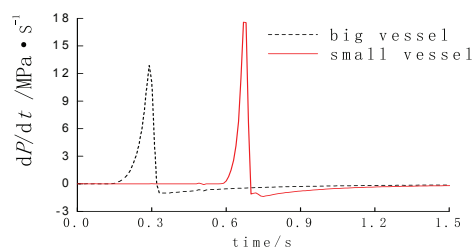


Fig. 3. Curve of rate of pressure rise in spherical vessels ignited in the center of vessels.

3.2. Size Effect of spherical vessels linked with pipes on explosion intensity

Experiments were implemented in the structure that a single spherical vessel linked with pipes, ignited in the center of the spherical vessel. Connection pipes are with the length of 0.25 m, 2.25 m, 4.25 m, 6.25 m respectively. The end of the pipes is plugged by a blind plate.

3.2.1. Size effect of the length of connection pipeline linked with one single spherical vessel on explosion intensity in spherical vessels

Fig. 4. and Fig. 5. show the influence of size due to the length of connection pipes on explosion intensity in spherical vessels. Table 1. shows the explosion intensity of methane-air mixture explosion in spherical vessels with 4 different lengths of pipes.

When one spherical vessel is linked with pipes, size effect on explosion intensity in the spherical vessel is obvious. The maximum explosion pressures in big vessel and small vessel both decrease with the increase of the length of connection pipes. And there is a good linear relationship between maximum explosion pressure and the length of connection pipes as follows, in big vessel: $P_{\max} = -0.02L + 0.702$, $R^2 = 0.94$; in small vessel: $P_{\max} = -0.035L + 0.683$, $R^2 = 0.966$.

The maximum rates of pressure rise in big and small vessels also both decrease with the increase of the length of connection pipes. And there is a good linear relationship between the maximum rate of pressure rise and the length of connection pipes as follows, in big vessel, $(dP/dt)_{\max} = -1.192L + 21.04$, $R^2 = 0.976$; in small vessel, $(dP/dt)_{\max} = -1.046L + 0.683$, $R^2 = 0.999$.

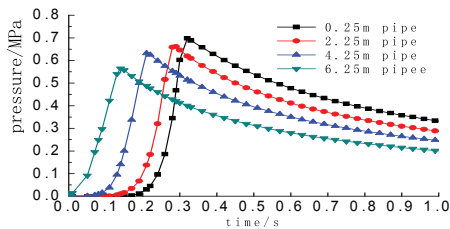


Fig. 4. Curve of pressure-time in big spherical vessel with different pipeline length.

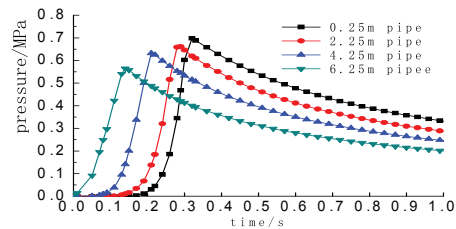


Fig. 5. Curve of pressure-time in small spherical vessel with different pipeline length.

Table 1. Methane-air mixture explosion intensity in vessel with different pipeline lengths

		0.25 m pipe	2.25 m pipe	4.25 m pipe	6.25 m pipe
big vessel	P_{\max}/MPa	0.689	0.662	0.632	0.565
	$(dP/dt)_{\max}/\text{MPa}\cdot\text{s}^{-1}$	13.813	11.603	9.708	7.469
small vessel	P_{\max}/MPa	0.687	0.580	0.545	0.463
	$(dP/dt)_{\max}/\text{MPa}\cdot\text{s}^{-1}$	20.869	17.882	16.6	13.55

After the flammable gas is ignited in the center of spherical vessels, the explosion is first formed in vessels, producing a huge number of energy, including high temperature and high pressure gas. Part of the energy ignites flammable gas in pipes and the rest of energy is decayed due to factors such as the wall. The cooling effect of the wall dominates in the structure made up with spherical vessel and pipes. So the longer the connection pipes, the more power losses due to the cooling effect of the wall. And the flammable gas is also increased accordingly with the increasing length of connection pipes, requiring more energy to ignite them. According to Law of Conservation of Energy, the explosion energy kept in spherical vessels became smaller, so maximum explosion pressure decreases correspondingly. However, because the diameter of the spherical vessels linked with pipes is different, the propagation process of the explosion wave in containers is different, resulting that the influence of the length of connection pipes on the maximum pressure in big vessel is smaller than that in small vessel, but the influence on the maximum rate of pressure rise in big vessel is much bigger than that in small vessel.

3.2.2. Size effect of the length of connection pipes linked with one spherical vessel on explosion intensity at the end of connection pipes

Monitoring dates of pressure sensors arranged on connection pipes show that maximum explosion pressure of the pipe always reach the highest value at the end of connection pipes. So the impact load at the end of the pipes is highest, and the risk is highest. Fig. 6. and Fig. 7. show the influence of the length of connection pipes on explosion intensity at the end of pipes. Table 2. shows the explosion intensity of gas at the end of pipes with 3 different lengths of pipes.

When connection pipes are linked with one vessel, the influences of size effect of the length of connection pipes on maximum explosion pressure at the end of pipes linked with big vessel and small vessel are opposite. In the case of the big vessel linked with connection pipes, the maximum explosion pressure at the end of connection pipes decreased gradually with an increasing length of connection pipes, the minimum value is 0.619 MPa, the maximum value is 0.721 MPa. In the case of the small vessel linked with connection pipes, the maximum explosion pressure at the end of connection pipes increase gradually with the increase of the length of connection pipes, the minimum value is 0.607 MPa, the maximum value is 0.727 MPa. And there is a good liner relationship between the maximum pressure and the length of the connection pipes linked with small vessel: $P_{\max}=0.03L+0.541$, $R^2=0.995$. The length of connection pipes also has size effect on the maximum rate of pressure rise at the end of pipes. In the case of the big vessel linked with pipes, the maximum rate of pressure rise at the end of connection pipes decreases first and then increases. While in the case of the small vessel linked with pipes, the maximum rate of pressure rise at the end of connection pipes increases with an increasing length of pipe, and there is a good liner relationship between the maximum rate of pressure rise and the length of connection pipes: $(dP/dt)_{\max}=0.973L-41.95$, $R^2=0.973$.

Therefore in the industrial production and safety critical design, it is necessary to choose the reaction containers with the appropriate diameter and pipes with appropriate length, avoid the size effect of the influence of the shock wave produced, control the reaction rate strictly, and prevent accidents.

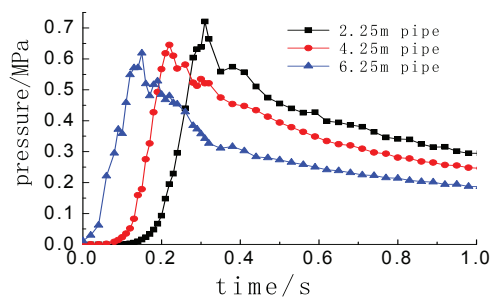


Fig. 6. Curve of pressure-time at the end of pipeline connected with the big vessel.

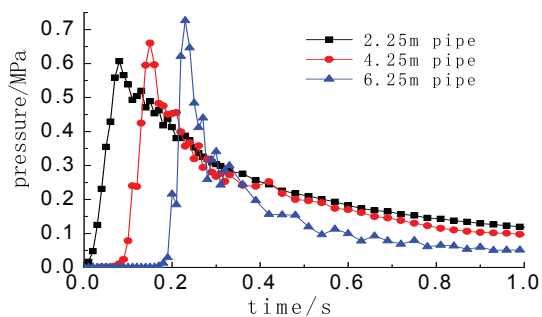


Fig. 7. Curve of pressure-time at the end of pipeline connected with the small spherical vessel.

Table 2. Gas explosion intensity at the end of pipeline after vessels linked pipelines

		2.25 m pipe	4.25 m pipe	6.25 m pipe
Big vessel	P_{\max}/MPa	0.721	0.645	0.619
	$(dP/dt)_{\max}/\text{MPa}\cdot\text{s}^{-1}$	46.719	31.646	48.425
Small vessel	P_{\max}/MPa	0.607	0.674	0.727
	$(dP/dt)_{\max}/\text{MPa}\cdot\text{s}^{-1}$	48.975	162.533	225.592

3.3. Size effect of the length of connection pipes in linked vessels on explosion intensity

Experiments were implemented in linked vessels (the small vessel, the big vessel, and connection pipes between two vessels). Flammable gas is ignited in the center of one spherical vessel which is called initiation container, another vessel is called secondary vessel. The lengths of connection pipes between two spherical vessels are 0.5 m, 2.5 m, 4.5 m and 6.5 m.

Figs. 8-11 show the influence of the lengths of connection pipes on explosion intensity in spherical vessels.

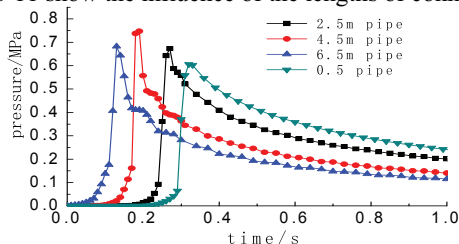


Fig. 8. Curve of pressure-time in big vessel ignited in the center of big vessel.

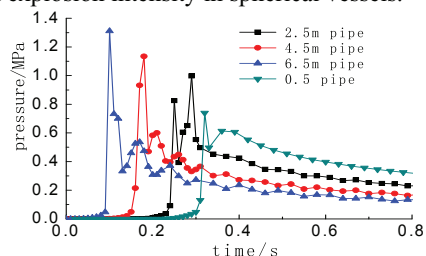


Fig. 9. Curve of pressure-time in small vessel ignited in the center of big spherical vessel.

Table3 shows the maximum rate of pressure rise in two vessels linked vessels with 4 different lengths of pipes.

Whether the big vessel or the small vessel is initiation vessel, the lengths of connection pipes all can produce size effect, exerting an influence on the explosion intensity in spherical vessels.

When ignited in the center of big vessel, the big vessel is initiating vessel, the small vessel is secondary vessel. When the length of connection pipes is 4.5 m, the maximum explosion pressure in initiating vessel (big vessel) reaches the highest value (0.747 MPa). Size effect due to the changes of the length of connection pipes also exerts an influence on the maximum rate of pressure rise in big vessel. The maximum rate of pressure rise in big vessel increases first and then decreases. When the length of connection pipes is 4.5 m, the maximum rate of pressure rise reaches the highest value ($94.11 \text{ MPa}\cdot\text{s}^{-1}$). However, the maximum explosion pressure in secondary vessel (small vessel) increases gradually with the increase of the length of connection pipes. And in secondary vessel (small vessel), there is a good liner relationship between the maximum explosion pressure and the length of connection pipes as follows: $P_{\max}=0.092L+0.722$, $R^2=0.982$.

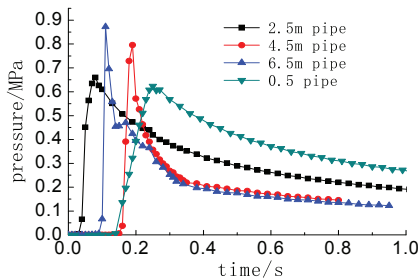


Fig. 10. Curve of pressure-time in big vessel ignited in the center of small vessel.

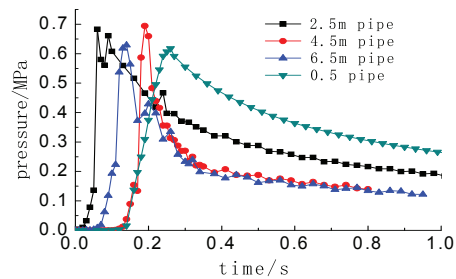


Fig. 11. Curve of pressure-time in small vessel ignited in the center of small vessel.

When ignited in the center of small vessel, the small vessel is initiating vessel, big vessel is secondary vessel. Size effect on explosion intensity due to the changes of length of connection pipes is obvious. The maximum explosion pressure in the initiating vessel (small vessel) increases first and then decrease. The highest value (0.747 MPa) is reached when the length of pipe is 4.5 m. Size effect due to the change of the length of connection pipes also has an influence on the maximum rate of pressure rise. The maximum rate of pressure rise increases with the increase of the length of connection pipes. The maximum explosion pressure in secondary vessel (big vessel) increases with the length of connection pipes. And there is a good liner relationship between the maximum explosion pressure in big vessel and the length of connection pipes are as follows, $P_{\max}=0.044L+0.583$, $R^2=0.960$.

Table 3 shows a law that the maximum rate of pressure rise in secondary vessel is faster than that in initiating container. And the maximum rate of pressure rise in secondary vessel increases with the increase of the length of connection pipes, a good liner relationships existing: big vessel as explosion transfer containers: $(dP/dt)_{\max}=38.57L+0.205$, $R_2=0.970$; small vessel as explosion transfer container: $(dP/dt)_{\max}=59.10L+130$, $R^2=0.959$.

Table 3. Maximum pressure rising rate in linked vessels

	ignited in the center of big spherical vessel (dP/dt) _{max} / $\text{MPa}\cdot\text{s}^{-1}$		ignited in the center of small spherical vessel (dP/dt) _{max} / $\text{MPa}\cdot\text{s}^{-1}$	
	big vessel	small vessel	big vessel	small vessel
0.5 m pipe	52.68	129.70	28.93	32.26
2.5 m pipe	94.11	316.71	94.06	76.59
4.5 m pipe	88.43	407.84	150.60	100.73
6.5 m pipe	63.99	493.33	267.22	108.05

According to the above analysis, in linked vessels, size effect of explosion intensity in secondary vessel is more obvious. In addition, when small vessel as secondary vessel, size effect is stronger, and both the maximum explosion pressure and maximum rate of pressure rise reach a high value which are bigger than the values in a single vessel. According to the stamping standards, the risk of small vessel increase sharply.

So when the industrial production and the design of anti-explosion and explosion venting involve linked vessels, it is must to avoid taking small vessel as the explosion transfer containers and to choose appropriate length of connection pips according the linear relationship between the explosion transfer containers and connection piping, and to control the risk within a safe range.

4. Conclusions

Through experiments and theoretical analysis, following conclusions about size effect of explosion intensity in spherical vessels and vessels can be drawn.

(1) When geometry size of single container is changed, the maximum explosion pressure remains unchanged, and the maximum rate of pressure rise decreases with the increase of the diameter of containers.

(2) With the increase of the length of connection pipes linked with one spherical vessel, the maximum explosion pressures and the maximum rates of pressure rise in big vessel and small vessel both decrease with linear relationships are as follows, in big vessel: $P_{\max} = -0.02L + 0.702$, $R^2 = 0.94$, $(dP/dt)_{\max} = -1.192L + 21.04$, $R^2 = 0.976$; in small vessel: $P_{\max} = -0.035L + 0.683$, $R^2 = 0.966$, $(dP/dt)_{\max} = -1.046L + 0.683$, $R^2 = 0.999$.

(3) At the end of connection pipes linked with big vessel, with the increase of the length of connection pipes, the maximum explosion pressure decreased gradually, and the maximum rate of pressure rise decreases first and then increase.

(4) At the end of connection pipes linked with small vessel, with the increase of the length of connection pipes, the maximum explosion pressure and the maximum rate of pressure rise both increase gradually as follows: $P_{\max} = 0.03L + 0.541$, $R^2 = 0.995$, $(dP/dt)_{\max} = 0.973L - 41.95$, $R^2 = 0.973$.

(5) The maximum explosion pressure and the maximum rate of pressure rise in secondary vessel all increase with the increase of the length of connection pipes, a good linear relationships existing: big vessel as explosion transfer containers: $P_{\max} = 0.044L + 0.583$, $R^2 = 0.960$, $(dP/dt)_{\max} = 38.57L + 0.205$, $R^2 = 0.970$; small vessel as explosion transfer container: $(dP/dt)_{\max} = 59.10L + 130$, $R^2 = 0.959$, $P_{\max} = 0.092L + 0.722$, $R^2 = 0.982$.

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